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ORIGINAL PAPER

Experimental evaluation of ceramic waste as filler in hot mix asphalt

Mohsen Shamsaei[1] · **Ramin Khafajeh**[1] · **Hosein Ghasemzadeh Tehrani**[1] · **Iman Aghayan**[1]

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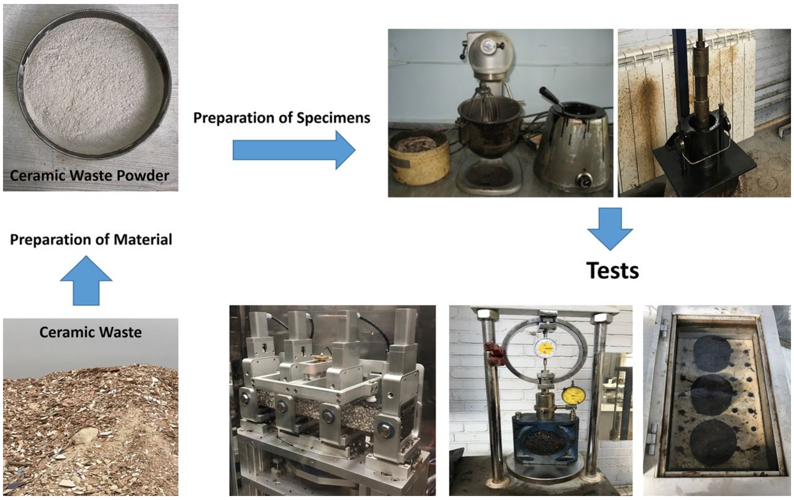
Abstract

Filler, as a component of hot mix asphalt, has an important role in improving the mechanical properties and extending the lifespan of asphalt. This research is conducted to evaluate the use of ceramic waste as filler and its effect on the mechanical properties of asphalt. For this purpose, ceramic waste powder was replaced with conventional limestone filler at 25%, 50%, 75%, and 100% proportions. Marshall stability, moisture sensitivity, four-point bending fatigue, and wheel track tests were used to investigate the effect of ceramic waste on asphalt performance. The results indicated that the Marshall stability was enhanced in all replacement ratios of the ceramic (23% increment for the maximum rate of substitution). Also, the resistance of the asphalt to moisture improved by approximately 5% after using 100% ceramic waste powder. In addition, the results showed that this rate of substitution as filler of HMA increased the fatigue life (approximately 600 cycles more than control specimens) and rutting resistance (reduction of almost 31% of the rut depth). Therefore, this waste material first improved the mechanical properties of HMA, and can also be used as a suitable approach for recycling this waste material.

Graphic abstract



Keywords Ceramic waste · Hot mix asphalt · Marshall stability · Moisture sensitivity · Fatigue life · Wheel track test

Introduction

The rapid growth of the traffic along with the increase in the axial load suggests the need for improving the quality of pavement materials. The characteristics of good pavements include smoothness, safety, durability, and being economical; it must also be capable of enduring anticipated loads.

✉ Hosein Ghasemzadeh Tehrani
h_ghasemzadeh@shahroodut.ac.ir

Extended author information available on the last page of the article

Filler, as a component of asphalt mixture, plays a major part in the functional properties of asphalt. Changes in the type and amount of filler may affect the properties of asphalt mix. Filler in asphalt is defined as fine mineral particles such as rock dust, hydrated lime, fly ash, and other suitable materials with a fraction size of less than 75 microns (ASTM D242 2009).

The majority of industries nowadays pose real threats to the environment in many ways. Meanwhile, waste materials are reported to be one of the most critical environmental problems. Further, excessive use of natural resources can wreak havoc on the natural environment including reduction in groundwater level, land degradation, and depletion of natural resources. Therefore, elimination of wastes and conservation of natural resources are of major significance (Woszuk et al. 2019a). For achieving these goals, several waste materials including reclaimed asphalt, waste of engine oil, steel slag, cross-linked polyethylene, and fly ash were used in different products to introduce some cleaner products (Maghool et al. 2017; Shamsaei et al. 2017; Woszuk et al. 2019b; Rodriguez-Fernandez et al. 2019; Ren and Sancaktar 2019).

Ceramic materials constitute one of the most substantial wastes which have a very low level of recycling. The production capacity of tile and ceramic in Iran is approximately 400 million m^2 per year which has placed Iran in the fifth rank in the world's ceramic and tile production. The amount of ceramic waste in different stages of production is about 3% to 7% of daily production (Shamsaei et al. 2019). Also, major parts of this waste material cannot be recycled. Thus, the most common way to deal with this waste is to keep it in landfills. The reason why ceramic waste is kept in these places is attributed to the absence of a suitable way to recycle it. Nevertheless, this method is not appropriate in terms of environmental issues and the cost of deposition. So, finding a suitable method to reuse ceramic waste is necessary. Although some research has been conducted for this purpose, the amount of recycled ceramic waste is negligible. Using this material in the construction industry, researchers can reuse high amounts of this waste to alleviate its environmental problems (Pacheco-Torgal and Jalali 2011).

The application of ceramic waste as raw materials in asphalt can be a novel method given the high amount of natural materials in asphalt pavements. For instance, the amount of asphalt production in European countries and in the USA reached approximately 285.5 and 374.9 million tons in 2016, respectively. Therefore, the construction of asphalt pavements demands high amounts of raw materials including filler and natural aggregates; the use of waste materials as an aggregate or filler of asphalt mixture can be a practical method for cleaner production (Woszuk et al. 2019a). Hence, ceramic waste can be used in asphalt mixture to recycle this material. This approach not only can reduce the amount of this waste considerably, but it may lower the consumption of natural aggregates and filler as non-renewable resources (Patel and Bhavsar 2016).

The effect of using ceramic waste aggregate (CWA) on asphalt mixture has been investigated in some studies. For example, Muniandy et al. (2018) investigated the asphalt mixture with ceramic as an aggregate. Ceramic waste was replaced with granite aggregate in different weight percentages of 0%, 20%, 40%, 60%, 80%, and 100%. The results indicated that the asphalt mixture containing 20% of waste ceramic as an aggregate had the best performance. Specifically, compared to control specimens, Marshall stability and resilient modulus strength of the specimens containing 20% ceramic waste increased by 25% and 13.5%, respectively.

In addition to ceramic waste as an aggregate, several studies have been carried out on using waste materials of other industries as filler of asphalt mixture. For instance, a study examined the effect of RHA and date seed ash (DSA) as filler in HMA. Specimens including 0%, 25%, 50%, 75%, and 100% were made, and some tests such as Marshall stability, Marshall quotient (MQ), indirect tensile stiffness modulus, four-point bending fatigue, and wheel track tests were conducted on them. The test results indicated that these materials enhanced the stability, fatigue life, and rutting resistance of HMA mixtures (Tahami et al. 2018).

According to the previous studies, a comprehensive study on using ceramic waste as filler of hot mix asphalt (HMA) has not been conducted. Thus, this research is performed to evaluate the impacts of different amounts of ceramic waste powder (CWP) on asphalt mixture. Accordingly, four different percentages of CWP were replaced with the conventional limestone filler. The Marshall stability, moisture sensitivity, four-point bending fatigue, and wheel track tests were performed. Accordingly, the effect of CWP on HMA was examined, and the results of these tests were compared with control mixtures.

Materials

Aggregates

In this study, the particle size distribution was determined in the Iran Highway Asphalt Paving Code-234 (2011). As shown in Table 1, limestone and mountain rock aggregates were used as coarse and fine aggregates, respectively. The maximum size of the coarse aggregates used was 19 mm. The materials passing through the sieve No. 4 (smaller than 4.75 mm) were selected as fine aggregates. The physical properties of materials used in this study are reported in Table 2.

Table 1 Particle size distribution of coarse and fine aggregates

Sieve size (mm)	Code-234	Passing percent (%)
19	100	100
12.50	90–100	95
4.75	44–74	59
2.36	28–58	43
0.30	5–21	13
0.075	2–10	6

Table 2 Physical properties of aggregate materials

Property	Standard	Mountain rock (fine agg.)	Limestone (coarse agg.)
Specific gravity (kg/m^3)	ASTM C127	–	2660
	ASTM C128	2600	–
Sand equivalent (%)	ASTM D2419	77	–
Fineness modulus (%)	ASTM C33	2.9	–
Los Angeles abrasion (%)	ASTM C131	–	22
Water absorption (%)	ASTM C127	–	0.53
	ASTM C128	2.2	–

Table 3 Physical properties of asphalt binder AC 60/70

Property	Standard	Result
Specific gravity (g/cm^3)	ASTM D70	1.1
Flash point (°C)	ASTM D92	256
Ductility (cm)	ASTM D113	104
Penetration at 25 °C (0.1 mm)	ASTM D5	66.3
Softening point (°C)	ASTM D36	51

Asphalt binder

The asphalt binder used to prepare the HMA was AC 60/70 manufactured in Tehran Oil Refinery. Table 3 shows the physical properties of the asphalt binder.

Filler

The filler used in this study included LS and CWP. The amount of consumed filler was 6% of the total mass of the aggregate materials. Ceramic waste was obtained from the wastes of the manufacturing process of Ronas Ceramic Factory in Semnan. The ceramic became powder with a ball mill machine. Figure 1 displays the size of this waste material which was smaller than 0.075 mm (No. 200 sieve).

The specific gravity of CWP was 2.64 g/cm^3. The limestone filler was used to prepare a control specimen. The limestone filler was obtained by crushing the lime aggregate material and was applied in a size smaller than 75 microns in the asphalt mixture with a specific gravity of 2.70 g/cm^3. Scanning electron microscopy (SEM) images of CWP and limestone filler for microscopic morphology of these particles were magnified 8000 and 100,000 times, as shown in Fig. 2. The surface of the CWP content is much rougher than that of the limestone content. Hence, the adsorption of CWP content is higher than that of the limestone filler. Further, high adsorption of CWP was investigated, and the specific surface areas of both CWP and limestone powder were measured as 544 cm^2/g and 443 cm^2/g, respectively. Hence, the adsorption of CWP was higher than that of limestone filler which can affect asphalt performance. The chemical compositions of LS and CWP are shown in Table 4 as measured by X-ray fluorescence (XRF).

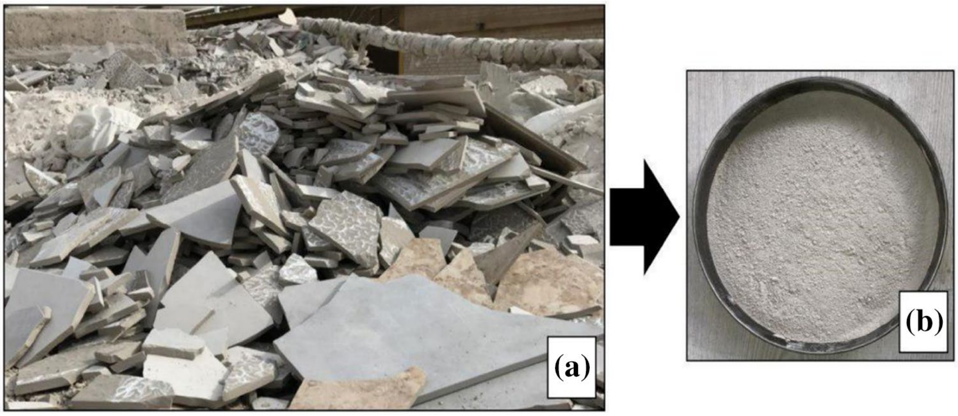


Fig. 1 Ceramic waste in the factory (**a**), the ceramic waste powder used as filler (**b**)

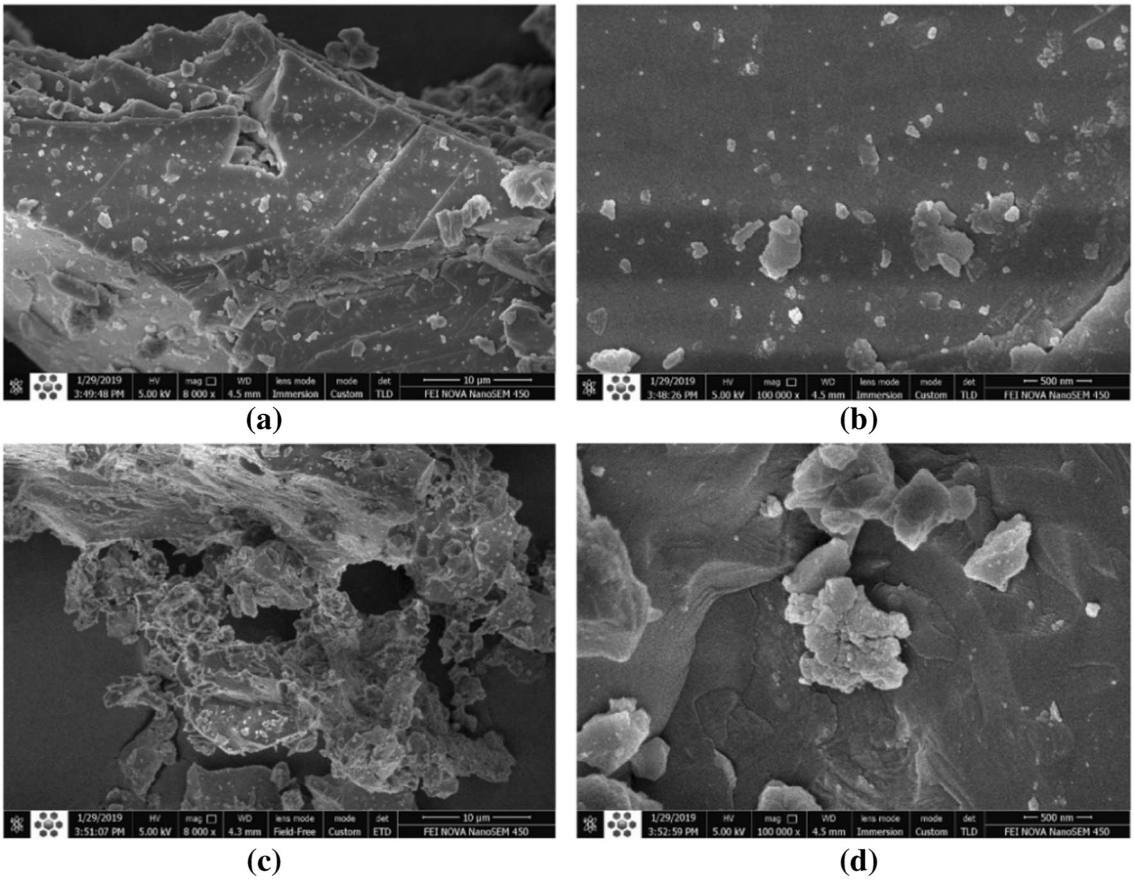


Fig. 2 SEM morphology; limestone powder with **a** 8000 × and **b** 100,000× magnification levels; CWP with **c** 8000× and **d** 100,000× magnification levels

Table 4 Chemical properties of ceramic waste and limestone filler

Composition (%)	Ceramic waste	Limestone powder
SiO_2	71.19	17.95
AL_2O_3	15.6	0.46
Fe_2O_3	3.2	0.052
MgO	1.28	3.64
TiO_2	0.7	0.03
P_2O_5	0.27	0.04
Na_2O	1.36	0.08
CaO	3.54	46.9
K_2O	1.98	0.10
LOI	0.86	29.95

Methods

The optimum asphalt binder content was determined by the Marshall method, and the HMA mix design was performed based on ASTM D1559 (1992). For this purpose, the aggregate materials were first heated at 160–170 °C. The asphalt binder temperature was set to 140–147 °C and mixed in a mixer. After pouring the asphalt mix into the Marshall mold, each side of the sample was hit by Marshall Hammer 75 times (for heavy traffic). Prior to the Marshall stability test, the specimens were placed in a hot bath of 60 °C for 30 min. To obtain the optimum asphalt binder, three asphalt samples were prepared for each asphalt binder percentage. In total, for each percentage of filler replacement, 15 asphalt samples were prepared with asphalt binder ratios of 4%, 4.5%, 5%, 5.5%, and 6%. The optimum asphalt binder content was determined based on the void of compressed asphalt, Marshall flow, Marshall stability, the void between the aggregate materials, and the void filled with asphalt binder. To achieve the optimum replacement ratio of ceramic waste filler in asphalt mixture, five different mixing plans were examined including LS and CWP. LS was considered as the control mix design. The proportions of asphalt mixtures containing different percentages of the ceramic waste and the optimum asphalt binder content for each mixing plan are shown in Table 5. These results indicated that as a result of increase

Table 5 Proportions of asphalt mixtures and optimum asphalt binder content

Mix type	Constituents (g)				Optimum bitumen (%)
	Filler		Fine aggregate (Mountain rock)	Coarse aggregate (Limestone)	
	(Limestone)	Ceramic			
LS (100%LS)	72	–	636	492	4.8
CWP25 (75%LS + 25%CWP)	54	18	636	492	5
CWP50(50%LS + 50%CWP)	36	36	636	492	5.2
CWP75 (25%LS + 75%CWP)	18	54	636	492	5.5
CWP100 (100%CWP)	–	72	636	492	5.7

in the CWP content, the optimum asphalt binder content increased. This can be a result of a specific surface area of CWP content. The specific surface area increased owing to the reduction in particle size, so this can elevate the optimum asphalt binder content.

Marshall stability and flow

The Marshall stability and flow tests were conducted on cylindrical samples with a diameter of 10.16 cm and a height of 6.35 cm according to ASTM D1559 (1992). This test was carried out at a temperature of 60 °C and applied the loading to the specimen at a constant rate of 50.8 mm/min.

Moisture sensitivity

Moisture sensitivity is one of the features of HMA with a significant impact on the performance and durability of asphalt. In this study, AASHTO T283 (2007) was used to investigate the moisture sensitivity. According to this method, six asphalt specimens were prepared for each mixing plan considering its optimum asphalt binder. Three specimens were prepared for the dry test, while the other three were used for testing under saturated conditions. The asphalt mixture was poured into the container and cooled down for 2 h at the ambient temperature. Further, the uncompacted asphalt mixture was placed in an oven at 60 °C for 16 h. Eventually, it was placed in an oven at the compression temperature prior to compression. Then, the asphalt mixture was compacted with a void percentage of 7%. The samples were in two groups of saturated and dry specimens. At this stage, a group of specimens was saturated between 70 and 80%. The saturated samples were put in a freezer at -18 °C for 16 h and finally in a water bath of 60 °C for 24 h. The moisture sensitivity of the asphalt mixture including the tensile strength ratio (TSR) index was obtained by Eq. 1 with respect to ITS of dry and saturated specimens (AASHTO T283).

$$\mathrm{TSR} = \frac{\mathrm{ITS}_{\mathrm{saturated}}}{\mathrm{ITS}_{\mathrm{dry}}} \tag{1}$$

In this equation, $\mathrm{ITS}_{\mathrm{saturated}}$ and $\mathrm{ITS}_{\mathrm{dry}}$ represent the ITS of saturated and dry specimens, respectively.

Wheel track test

Rutting is as considered one of the important factors which can reduce the long-term performance of asphalt (Zou et al. 2017). In this research, the wheel track test was conducted with the aim of determining the permanent deformations and resistance of asphalt mixtures against them. This test was applied at critical temperatures and under equal loads in relation to real situations. Indeed, the number of passes to failure and the rut depth were determined. The regulation of this test is based on BS 598: Part 110 (1996). The dimension of specimens was 300 × 300 × 50 mm, and the temperatures were 40 and 50 °C. Loading 700 Newton with a period of 10,000 cycles was applied.

Four-point bending fatigue test

Fatigue is perceived as one of the most important phenomena which can shorten the lifespan of pavements. This occurs by micro-cracks on the asphalt layer which will expand gradually and reach the upper layers of the pavement (Moghadas Nejad et al. 2013). The fatigue life has been measured according to AASHTO T321 (2017). The specimens were made in a beam shape with dimensions of 480 × 50 × 50 mm. For this test, the frequency was 10 Hz and the strain level of the strain-controlled mode was 600 microstrains. The temperature was constant at 20 °C, and specimens were placed for at least 5 h in the control chamber to reach this temperature before initiating the test. The fatigue life was measured when the stiffness of specimens decreased by 50%.

Results and discussion

Marshall stability

Marshall stability demonstrates the stability and ability of the pavement to resist rutting. Table 6 shows that the

Table 6 Results of the Marshall test

Mix type	Marshall stability (kg)		Flow (mm)		Air voids (%)		MQ (KN/mm)
	Test	Code-234	Test	Code-234	Test	Code-234	
LS	1201	800	3.35	2–3.5	4.37	3–5	3.58
CWP25	1245	800	3.21	2–3.5	4.22	3–5	3.87
CWP50	1253	800	3.02	2–3.5	4.1	3–5	4.14
CWP75	1383	800	2.86	2–3.5	3.94	3–5	4.83
CWP100	1486	800	2.61	2–3.5	3.74	3–5	5.7

Marshall stability was improved by raising the ceramic replacement ratio. The Marshall stability was higher compared to that of the control specimen at all replacement ratios of the ceramic waste. The maximum Marshall stability was observed at a replacement ratio of 100%, with an improvement of 23% compared to the specimen with limestone filler. The minimum Marshall stability is 800 kg in accordance with the Iran Highway Asphalt Paving Code-234 (2011). The Marshall stabilities were higher than 800 kg at all replacement ratios. The increase in Marshall stability after using CWP can be a result of the lower specific gravity of CWP content in comparison with that of limestone. This suggested that the volume of CWP content in the asphalt mixture was greater than the volume of the same weight percentage of the limestone content in the mixture. Also, the higher volume of the filler content showed higher adsorption of the asphalt binder. This can lead to stronger adhesion between asphalt binder and aggregates, thereby significantly enhancing the load-bearing capacity of HMA. According to Table 6, the Marshall flow parameter, air void, and Marshall stability for the asphalt mixtures are within the permissible ranges specified in the Iran Highway Asphalt Paving Code-234 (2011).

The variations in flow values for five different mixtures are shown in Table 6. The minimum flow value demonstrated the brittle behavior, while the maximum flow value indicated the maximum plasticity of asphalt (Asphalt Institute 1993). The filler type has a direct impact on the stiffness of the asphalt mixture (Hesami 2014). The test results showed that specimens containing 100% CWP had the minimum flow. So, the stiffness of asphalt mixture for these specimens increased significantly.

The void is considered as one of the most important factors in asphalt mixtures, and asphalt binder content has an inverse relationship with this factor (Akbulut et al. 2011). The usage of CWP as filler increased the optimum asphalt binder which can decrease the air voids. So, according to the results of Table 6, the air voids were decreased and the Marshal stability was enhanced.

The strength of the materials against permanent deformation is measured by MQ. This parameter is calculated as the ratio of Marshall stability (kN) to Marshall flow (mm) (Aghayan and Khafajeh 2019). As shown in Table 6, 100% CWP and 100% conventional limestone filler constituted the highest and the lowest MQ, respectively.

Moisture sensitivity

Figure 3 reveals the moisture sensitivity test results according to AASHTO T283 (2007). As shown in Fig. 3, CWP improved the moisture sensitivity properties of the asphalt mixtures compared to the conventional limestone filler. The highest growth in the moisture sensitivity was observed at 100% ceramic replacement leading to a 5% improvement compared to the control specimen. Note that the minimum allowable TSR is 80%. At higher TSR, the asphalt mixture showed more resistance to moisture. According to the results, the TSR values were above 80% at all replacement ratios.

Regarding the XRF test results given in Table 4, the amounts of acidic oxides in the ceramic waste (i.e., iron oxide, Fe_2O_3; aluminum oxide, Al_2O_3; silicon dioxide, SiO_2) were totally about 90%. This was higher than the allowable percentage (70%) mentioned in ASTM C618 (2015). This suggested that the pozzolanic property of ceramic was greater than that of limestone. Therefore, enhanced moisture resistance of asphalt mixtures containing CWP can be as a result of higher pozzolanic nature of ceramic compared to limestone. This attribute can increase the adhesion between aggregates and asphalt binder (Hefer 2004).

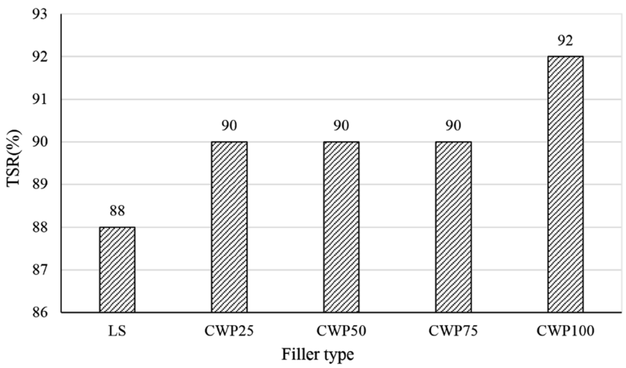


Fig. 3 Moisture sensitivity test results for specimens containing ceramic and limestone fillers

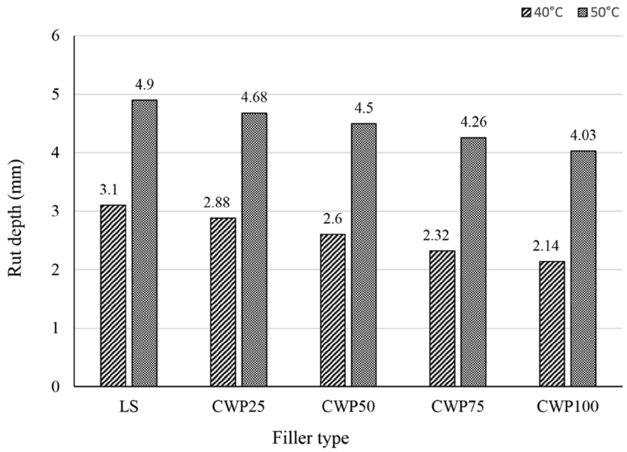


Fig. 4 Rutting resistance of HMA with ceramic and limestone fillers

Wheel track test

The wheel track test of all specimens is shown in Fig. 4. The rut depth measured in control specimens was considerably higher than the value of the rut depth in the samples containing CWP. This suggested that after replacing limestone filler with CWP, the strength increased against permanent deformation. The highest resistance against permanent deformation was observed for 100% replacement of limestone filler with CWP. The impacts of temperatures on asphalt mixture are shown in Fig. 4. After elevating the temperature, the values of rut depth increased for both specimens containing limestone filler and CWP. However, the development of rut depth for specimens containing CWP was less than that of control specimens. Thus, the use of CWP as filler reduced the temperature sensitivity of HMA.

The results of the wheel track and MQ tests had a good correlation. Indeed, rutting behavior can be estimated from MQ values. So, specimens with a higher MQ show better resistance against rutting (Hinislioglu and Agar 2004). Mixtures with higher MQ values, because of their stiffness, have a better ability to distribute the loads (Aghayan and Khafajeh 2019). Hence, specimens containing CWP, due to higher stiffness, can present better anti-rutting performance in hot weather (Rodriguez-Fernandez et al. 2019).

Fatigue test

The fatigue life for all mixtures is shown in Fig. 5. According to the test results, the use of CWP as filler can enhance the fatigue life of HMA. Indeed, the increase in the percentage of CWP enhanced fatigue life with the maximum fatigue life being observed for total substitution of limestone filler with this waste material. This enhancement can be due to the increased adhesion between aggregate and asphalt binder. The adsorption of the asphalt binder and surface area of the filler is directly interrelated (Chen et al. 2011). The surface area of the CWP is greater than that of the limestone filler due to finer particles of CWP. The adsorption ability of CWP content was greater than that of the conventional filler which can lead to better interaction between the surface of the aggregate and asphalt binder. Indeed, the bonding quality and asphalt binder–aggregate interaction can be improved considerably (Cerato and Lutenegger 2002). Thus, the overall performance of the asphalt mixture can be enhanced as a result of better interaction between the asphalt binder and aggregates.

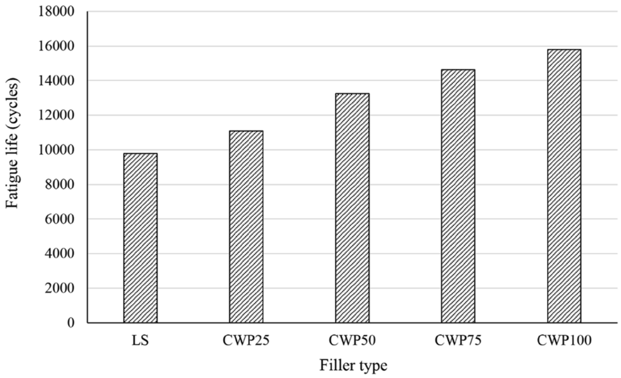


Fig. 5 Fatigue resistance of HMA with ceramic and limestone fillers

Conclusions

The main purpose of this study was to evaluate the usage of ceramic waste as filler in HMA mixture. The mechanical properties of the asphalt mixture revealed that the ceramic waste can be used as filler. In addition to improve the mechanical properties, the reuse of non-recyclable ceramic waste can reduce the environmental impact of ceramic waste. The reason is that high amounts of this waste material can be used as filler of HMA. This approach not only can reduce the demand for natural materials as non-renewable resources, but it can also lower the costs of landfills. The results of Marshall stability and flow tests revealed that CWP improved the Marshall stability at all filler replacement ratios. The maximum Marshall stability was observed at 100% ceramic powder replacement, leading to a 23% improvement in Marshall stability compared to the specimen with limestone filler. Also, after using this waste material, the MQ of specimens increased, and specimens containing 100% CWP had the maximum MQ. Considering the results of the moisture sensitivity test, the moisture properties of the asphalt mixture was improved by the ceramic replacement. The maximum growth in TSR was obtained at 100% replacement offering a 5% improvement compared to the control specimen. Moreover, the wheel track test indicated that adding ceramic waste as filler of the asphalt mixture can enhance its rutting resistance. The specimens with 100% CWP had the lowest rut depth (almost 31% lower than the control specimens) and led to their improved permanent deformation. Further, CWP reduced the thermal sensitivity of asphalt mixture compared to the control specimen. Also, the fatigue behavior of the asphalt mixture was improved by CWP, and the highest fatigue life was observed for 100% substitution of CWP (approximately 1600 cycles). Finally, according to the results, the asphalt mixture containing ceramic waste as filler showed a suitable performance. Therefore, the usage of this waste material as filler of HMA can be recommended because of its environmental benefits and mechanical effects on HMA.

Compliance with ethical standards

Conflict of interest The authors declare no conflict of interest.

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Affiliations

Mohsen Shamsaei[1] · Ramin Khafajeh[1] · Hosein Ghasemzadeh Tehrani[1] · Iman Aghayan[1]

Mohsen Shamsaei
M.shamsaei50@gmail.com

Ramin Khafajeh
C.R.Khafajeh@gmail.com

Iman Aghayan
iman.aghayan@shahroodut.ac.ir

[1] Faculty of Civil Engineering, Shahrood University of Technology, Shahrood, Iran